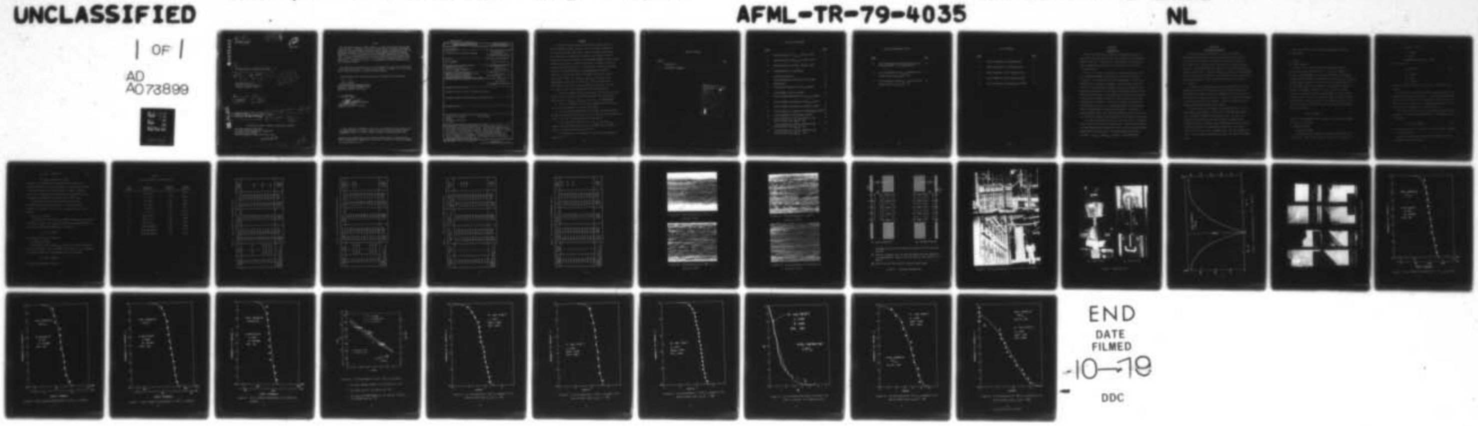
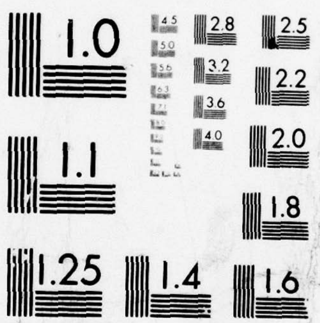
AD-A073 899 WASHINGTON UNIV ST LOUIS MO MATERIALS RESEARCH LAB F/G 11/4
FATIGUE FAILURE OF COMPOSITE LAMINATES.(U)
APR 79 N Q NGUYEN, J L KARDOS F33615-77-C-5053
UNCLASSIFIED AFML-TR-79-4035 NL

| OF |

AD
A073899



END
DATE
FILMED
10-79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

18 19

AFML-TR-79-4035

6

FATIGUE FAILURE OF COMPOSITE LAMINATES

10 Nhan Q. Nguyen
J. L. Kardos

Washington University
Materials Research Laboratory
St Louis, Missouri 63130

11 April 1979

12 36p.

Technical Report AFML-TR-79-4035
9 Interim Report, for Contract F33-77-C-5053
Period May 1977 to April 1978

15 F33615-77-C-5053

16 2419 17 03

Approved for public release; distribution unlimited

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

408186

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

S. W. TSAI, Project Engineer & Chief
Mechanics & Surface Interactions Br.
Nonmetallic Materials Division

FOR THE COMMANDER

J. M. KELBLE, Chief
Nonmetallic Materials Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFML/MBM, W-PAFB, OH 45433 to help us maintain a current mailing list".

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFML-TR-79-4035	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Fatigue Failure of Composite Laminates		5. TYPE OF REPORT & PERIOD COVERED Interim Report May 1977-April 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Nhan Q. Nguyen, J. L. Kardos		8. CONTRACT OR GRANT NUMBER(s) F33615-77-C-5053
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington University, Materials Research Laboratory, St Louis, Missouri 63130		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 24190314 (formerly 2307P107)
11. CONTROLLING OFFICE NAME AND ADDRESS Mechanics & Surface Interactions Branch, Nonmetallic Materials Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE April 1979
		13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

graphite epoxy laminates
fatigue
statistical distribution
S-N curves
static strength

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program is to provide fatigue data on a graphite-epoxy composite. AS/3501-5A was selected as the test material. Unidirectional composites with 0 and 90 degree ply orientations were tested. Both static and fatigue strength were measured. Multidirectional laminates with ± 45 and $0_2/90/\pm 45$ ply orientations were also tested. The fatigue data were analyzed using Weibull parameters. The frequency of testing was kept low in order to limit the temperature use below 5°C. More extensive data will be generated and analyzed under this contract.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

79 09 17 019

FOREWORD

The material presented herein constitutes the annual report for Contract F33615-77-C-5053, "Fatigue Failure of Composite Laminates", for the period from May 1977 to April 1978. The overall objective of this program was to conduct basic research on the fatigue failure of composite laminates as a function of environmental exposure and the history of loading, including the effects of load level, frequency, sequencing, random loading, and compression. The program was originated to provide a coherent, reliable data base for the graphite/epoxy material, AS/3501-5A, which has been selected for design use by the Air Force. Four laminate layups, i.e. $[0°]_{6\ ply}$, $[90°]_{8\ ply}$, $[\pm 45°]_{2s}$, and $[0/0/90/\pm 45]_s$, were chosen for this study, and the laminate plates fabricated at the University of Dayton Research Institute. Over the first year of effort, the following results have been obtained.

1. The static tensile strength distributions have been statistically defined in terms of Weibull distribution parameters for the following four laminates: $[0°]_{6\ ply}$, $[90°]_{8\ ply}$, $[\pm 45°]_{2s}$, and $[0/0/90/\pm 45]_s$.

2. The S-N relationship for a $[\pm 45°]_{2s}$ laminate has been defined in terms of both logarithmic and power law equations.

3. The life time distributions of the $[\pm 45]_{2s}$ laminate have been defined at each applied stress level, as well as for the entire normalized curve, in terms of a two-parameter Weibull distribution.

4. The lifetime distributions of the $[0°]_{6\ ply}$ and $[90°]_{8\ ply}$ laminates have been defined at 90% of their average static strengths in terms of a two-parameter Weibull distribution.

5. The temperature rise throughout the fatigue testing reached a maximum of 5°C.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

SECTION I

INTRODUCTION

Over the last ten years, a number of high-temperature modified epoxy resins have been developed for use as matrices in high performance composite materials. These materials were developed to withstand the high use temperatures encountered by high speed aircraft and other military hardware.

The U. S. Air Force is now making an increasing commitment to the use of advanced composites in strength-critical, safety-of-flight structures. In so doing, proven life cycle durability is likely to be required prior to production acceptance. Any such durability analysis will have to include load-environmental effects on an accelerated time frame basis because real-time and expense considerations make full-scale proof testing infeasible. To implement such an analysis, the time frame will have to be truncated and there will have to be some sort of test verification of the analysis. The critical element in providing the needed durability analysis is a reliable data base which includes the effects of combined moisture-thermal environments. In addition to providing design inputs, such a data base would also serve as a specifications guideline to quality control each step as the material is processed.

This report summarizes the results of the first year of a three-year effort to provide a reliable fatigue data base. Experimental procedures are described and results presented for static tensile tests and uniaxial tension-tension fatigue tests on four graphite/epoxy (AS/3501-5A) laminates: $[0°]_{6\ ply}$, $[90°]_{8\ ply}$, $[\pm 45°]_{2s}$, and $[0/0/90/\pm 45]_s$.

SECTION II

EXPERIMENTAL PROCEDURE

The prepreg material selected for this study is AS/3501-5A graphite/epoxy manufactured by Hercules, Incorporated. The standard cure cycle with the exception of the post cure was used to fabricate 61 cm (24") by 61 cm sample plates at the University of Dayton Research Institute. Three sample plates were fabricated for each of the following laminate configurations: $[0°]_{6\ \mathrm{ply}}$, $[90°]_{8\ \mathrm{ply}}$, $[\pm45°]_{2s}$, and $[0/0/90/\pm45]_s$. Table I lists the specific gravity and resin content for each sample plate. The photomicrographs for these laminate plates are shown in Figures 1a, 1b, 1c, and 1d.

All tensile static and tension-tension fatigue specimens were 2.5 cm (0.98") wide and 15 cm (5.91") long with 7.5 cm (2.95") of gage section. Each specimen was tabbed using 0.16 cm (0.0625")-thick glass epoxy, and was divided into 5 zones, namely A, B, C, D, and E, to specify the location of the failure surface in each specimen. Figure 2 illustrates the test specimen construction and the zone designation.

Static tensile tests were done on twelve specimens for each of the four laminate configurations. Three of the 12 specimens were mounted with strain-gages to determine the Poisson's ratio. All tests were performed on a MTS machine under load control at a loading rate of 89 N/sec (20 lb/sec). Tension-tension fatigue tests were also performed under load control on the eletrohydraulic eight-station test frame (Figure 3). The stress ratio in fatigue was 0.1, and the frequency was 2/3 Hz. Figure 4 shows the mounting jigs used in the static and fatigue tests.

Data acquisition for all tests was accomplished with a PDP-8 on-line computer.

1. Results

a. Static Properties:

Tables 2, 3, 4, and 5 list the tensile static test results for the four laminate configurations, i.e. $[0°]_{6\ ply}$, $[90°]_{8\ ply}$, $[\pm 45°]_{2s}$, and $[0/0/90/\pm 45]_s$. A least-squares linear fit was employed to obtain the longitudinal stiffness modulus for the $[0°]_{6\ ply}$, $[90°]_{8\ ply}$, and $[0/0/90/\pm 45]_s$ specimen, as well as the initial tangent modulus, E_o, for the $[\pm 45°]_{2s}$ specimen. The Poisson's ratios were also obtained through a least-squares linear fit of the ε_L-ε_{LT} data. A typical stress-strain response of $[\pm 45°]_{2s}$ graphite/epoxy in uniaxial static tension is shown in Figure 5. The failure modes for the four laminate configurations are shown in Figure 6. The probability of survival (S) for each laminate is obtained by fitting the data with a two-parameter Weibull distribution:

$$S = \exp\left[-(X/\hat{X}_o)^{\alpha} \right] \qquad (1)$$

where X is the experimental static strength. The results are plotted in Figures 7, 8, 9, and 10.

b. Fatigue Properties:

1) $[\pm 45°]_{2s}$ Laminate:

The fatigue life of the $[\pm 45°]_{2s}$ laminate was determined at four stress levels. The S-N data, Figure 11, were fit by a straight line,

$$S_{max}/\hat{X}_o = m \log N + b \qquad (2)$$

$m = -0.0752$,

$b = 1.035$,

Standard Deviation (STD) = 0.026

and by a power law,

$$S_{max}/\overline{X}_o = cN^d \qquad (3)$$

$d = -0.0434$,

$c = 1.096$,

STD. = 0.029

where $\hat{X}_o$ is obtained from Equation (1) and $\overline{X}_o$ is the average static strength.

The temperature change during fatigue, which was recorded with a temperature strain gage, was under 5°C. The fatigue failure mode was not much different from the static failure mode. Under a low stress fatigue ratio, i.e. $S_{max}/\hat{X}_o < 0.7$, delamination of the outer ply was observed only a few cycles prior to ultimate failure.

The probability of survival, S_f, at each applied stress level is obtained by fitting the fatigue life data with a two parameter Weibull distribution:

$$S_f = \exp [-(N/\hat{N}_o)^{\alpha}] \qquad (4)$$

The results are plotted in Figures 12, 13, and 14 and show a reasonable fit of the distribution.

Scatter in the pooled life data was also analyzed by using a two-parameter Weibull distribution:

$$R_f = \exp\left[- (\overline{N}/\hat{N})^{\alpha_f} \right] \qquad (5)$$

$$\overline{N} = N/N_{th} \text{ (normalized life data)}$$

where N_{th} is the predicted life from Equation (3) and R_f is the probability of the life being longer than N. The results are plotted in Figure 15 along with all the normalized life data. The curve shows a fairly reasonable fit even though the shape parameter α_f was assumed to be independent of the applied stress level, S_{max}.

Using Equations (3) and (5), we can obtain a S-N curve corresponding to any desired reliability. A S-N curve for 90% probability of survival, i.e. $R_f = 0.9$, is shown in Figure 11 as an example.

2) $[0°]_{6\ ply}$ Laminate.

The fatigue life of the $[0°]_{6\ ply}$ laminate was obtained at an applied stress level $S_{max}/\hat{X}_o \simeq 90\%$, and was fitted with a two-parameter Weibull distribution to obtain the probability of survival, S_f:

$$S_f = \exp\left[-N/\hat{N}_o)^{\alpha} \right]$$

The results are plotted in Figure 16.

3) $[90°]_{8\ ply}$ Laminate.

The fatigue life of the $[90°]_{8\ ply}$ laminate was done at the applied stress level $S_{max}/\hat{X}_o \simeq 90\%$. The probability of survival, S_f, was obtained by fitting the data with a two-parameter Weibull distribution:

$$S_f = \exp\left[-(N/\hat{N}_o)^{\alpha} \right]$$

The results are plotted in Figure 17.

TABLE 1

Physical Properties of Laminate Plates

Plate Number	Laminate Orientation	Specific Gravity	% Resin Content
1	0°, 6 ply	1.62	26.28
2	0°, 6 ply	1.63	26.66
3	0°, 6 ply	1.62	26.93
4	0°, 8 ply	1.62	26.83
5	0°, 8 ply	1.62	27.72
6	0°, 8 ply	1.61	26.75
7	$\pm 45°$, 8 ply	1.61	27.14
8	$\pm 45°$, 8 ply	1.61	27.80
9	$\pm 45°$, 8 ply	1.59	29.91
10	$[0°/0°/90°/\pm 45°]_s$	1.60	30.22
11	$[0°/0°/90°/\pm 45°]_s$	1.62	27.12
12	$[0°/0°/90°/\pm 45°]_s$	1.61	27.28

Table 2. Static Properties of 0° Laminate (6 ply)

Specimen Number	Failure Zone	Ultimate Stress GPa (ksi)	Ultimate Strain, in/in	E_L GPa (10^3 ksi)	Poisson's Ratio
3-A1	A	1.570 (227.7)	0.0122	129.3 (18.75)	-
3-A2	A	1.358 (197.0)	0.0110	123.4 (17.90)	-
3-A3	A	1.508 (218.7)	0.0118	127.3 (18.47)	-
3-A4	End of Tab	1.335 (193.6)	0.0105	127.3 (18.46)	-
3-A5	A	1.425 (206.7)	0.0106	134.4 (19.50)	0.271
3-A6	B	1.552 (225.1)	0.0121	128.5 (18.64)	-
3-A7	C	1.384 (200.7)	0.0107	129.2 (18.74)	-
3-A8	End of Tab	1.366 (198.1)	0.0111	122.7 (17.80)	0.244
3-A9	End of Tab	1.344 (195.0)	0.0104	129.4 (18.77)	-
3-A10	End of Tab	1.309 (189.8)	0.0102	128.4 (18.63)	-
3-A11	End of Tab	1.442 (209.1)	0.0111	129.3 (18.75)	0.271
3-A12	C	1.444 (209.5)	0.0111	129.8 (18.83)	-
Average		1.420 (205.9)	0.0111	128.3 (18.60)	0.262
Standard Deviation		0.086 (12.53)	0.0007	3.031 (0.440)	0.016
Coefficient of Variation		6.09%	5.95%	2.36%	6.00%

Table 3. Static Properties of 90° Laminate (8 ply)

Specimen Number	Failure Zone	Ultimate Stress MPa (ksi)	Ultimate Strain, in/in	E_L GPa (10^3 ksi)	Poisson's Ratio
6-A1	A	58.58 (8.496)	0.0077	7.632 (1.107)	0.0146
6-A2	C	55.76 (8.088)	0.0068	8.157 (1.183)	-
6-A3	End of Tab	49.28 (7.148)	0.0056	8.784 (1.274)	0.0169
6-A4	End of Tab	48.47 (7.030)	0.0060	8.122 (1.178)	0.0140
6-A5	End of Tab	59.77 (8.669)	0.0075	7.922 (1.149)	-
6-A6	A	47.06 (6.825)	0.0060	7.888 (1.144)	-
6-A7	A	66.42 (9.633)	0.0085	7.791 (1.130)	-
6-A8	A	61.24 (8.882)	0.0076	8.032 (1.165)	-
6-A9	End of Tab	55.32 (8.023)	0.0070	7.888 (1.144)	-
6-A10	End of Tab	59.78 (8.670)	0.0074	8.074 (1.171)	-
6-A11	End of Tab	56.11 (8.138)	0.0068	8.205 (1.190)	-
6-A12	C	55.61 (8.066)	0.0073	7.667 (1.112)	-
Average		56.12 (8.139)	0.0070	8.013 (1.162)	0.0152
Standard Deviation		5.668 (0.822)	0.0008	0.305 (0.044)	0.0015
Coefficient of Variation		10.1%	11.9%	3.8%	10.2%

Table 4. Static Properties of $\pm 45°$ Laminate (8 ply)

Specimen Number	Failure Zone	Ultimate Stress MPa (ksi)	Ultimate Strain, in/in	Initial Tangent Modulus, E_o GPa (10^3 ksi)	Poisson's Ratio
9-A1	B	176.3 (25.57)	0.0235	15.66 (2.272)	-
9-A2	A	172.9 (25.08)	0.0230	15.36 (2.228)	-
9-A3	A	179.7 (26.06)	0.0247	15.14 (2.195)	0.782
9-A4	B	180.6 (26.20)	0.0266	18.72 (2.715)	0.725
9-A5	B	180.0 (26.11)	0.0324	16.26 (2.358)	0.804
9-A6	C	184.5 (26.76)	0.0349	16.04 (2.326)	-
9-A7	C	182.8 (26.51)	0.0313	16.38 (2.376)	-
9-A8	C	182.0 (26.40)	0.0296	16.30 (2.364)	-
9-A9	C	186.5 (27.05)	0.0261	15.74 (2.283)	-
9-A10	C	187.5 (27.20)	0.0350	15.80 (2.292)	-
9-A11	B	187.9 (27.25)	0.0335	16.01 (2.321)	-
9-A12	B	189.6 (27.50)	0.0423	15.83 (2.296)	-
Average		182.5 (26.47)	0.0302	16.10 (2.336)	0.770
Standard Deviation		4.981 (0.722)	0.0058	0.904 (0.131)	0.041
Coefficient of Variation		2.7%	19.1%	5.6%	5.3%

Table 5. Static Properties of $[0/0/90/\pm45]_s$ Laminate

Specimen Number	Failure Zone	Ultimate Stress MPa (ksi)	Ultimate Strain, in/in	E_L GPa (10^3 ksi)	Poisson's Ratio
12-A1	C	697.1 (101.1)	0.0116	60.03 (8.706)	0.304
12-A2	A	638.9 (92.67)	0.0105	60.83 (8.823)	-
12-A3	B	651.4 (94.48)	0.0113	57.89 (8.396)	0.310
12-A4	B	729.5 (105.8)	0.0119	61.02 (8.850)	-
12-A5	A	633.9 (91.94)	0.0109	58.34 (8.461)	0.317
12-A6	A	715.7 (103.8)	0.0122	58.43 (8.474)	-
12-A7	B	637.2 (92.42)	0.0110	58.01 (8.414)	-
12-A8	A	618.0 (89.63)	0.0112	55.28 (8.017)	-
12-A9	B	643.6 (93.35)	0.0117	54.97 (7.972)	-
12-A10	B	615.2 (89.23)	0.0114	53.82 (7.806)	-
12-A11	B	628.5 (91.15)	0.0107	58.60 (8.499)	-
12-A12	A	610.2 (88.50)	0.0107	57.10 (8.281)	-
Average		651.6 (94.51)	0.0113	57.86 (8.392)	0.310
Standard Deviation		40.10 (5.815)	0.0005	2.268 (0.329)	0.006
Coefficient of Variation		6.2%	4.7%	3.9%	2.0%

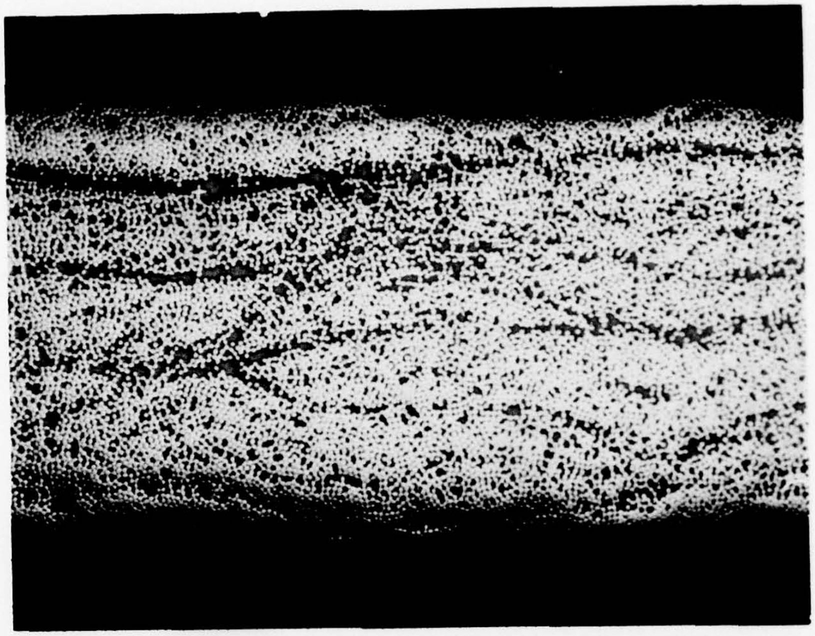


FIGURE 1a. PHOTOMICROGRAPH OF $[0^\circ]_{6\ ply}$ LAMINATE (100X).

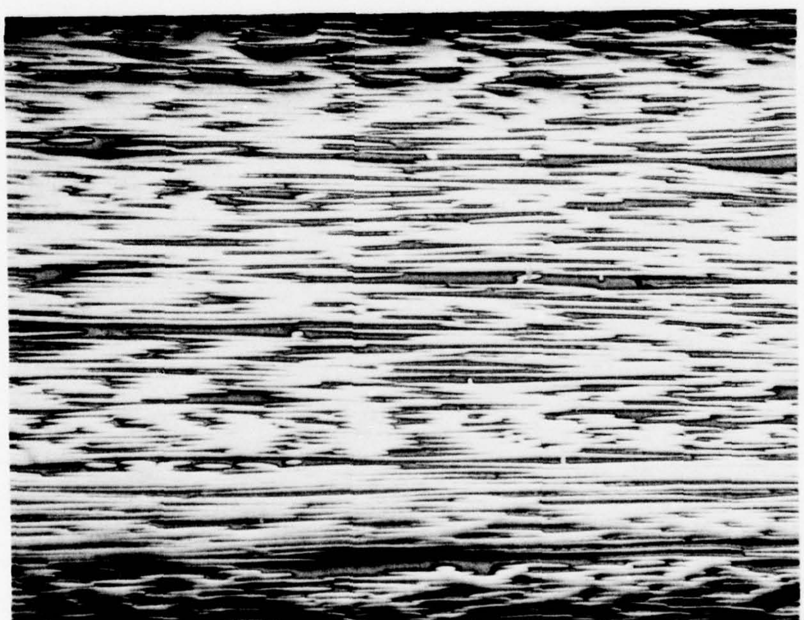


FIGURE 1b. PHOTOMICROGRAPH OF $[90^\circ]_{8\ ply}$ LAMINATE (100X).

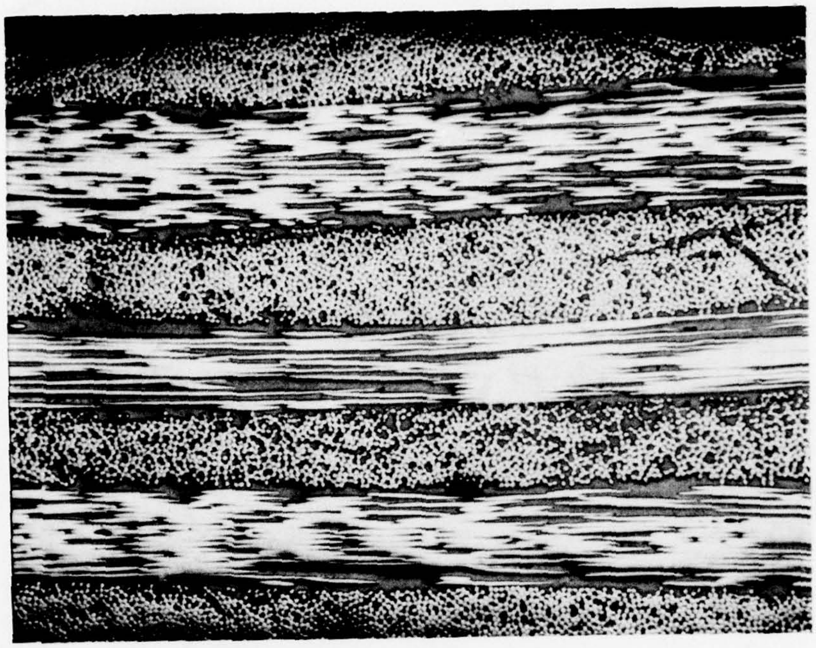


FIGURE 1c. PHOTOMICROGRAPH OF [$\pm 45^{\circ}$]$_{2S}$
LAMINATE (100X).

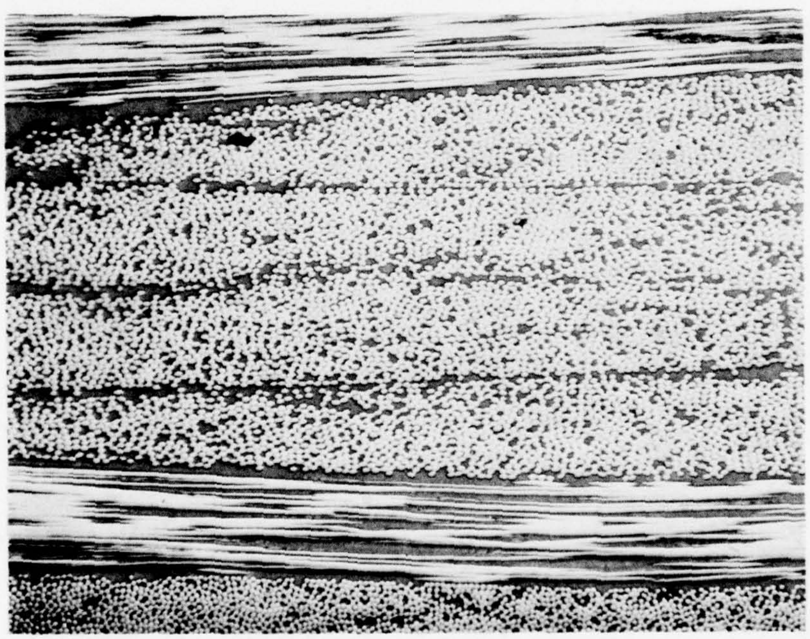
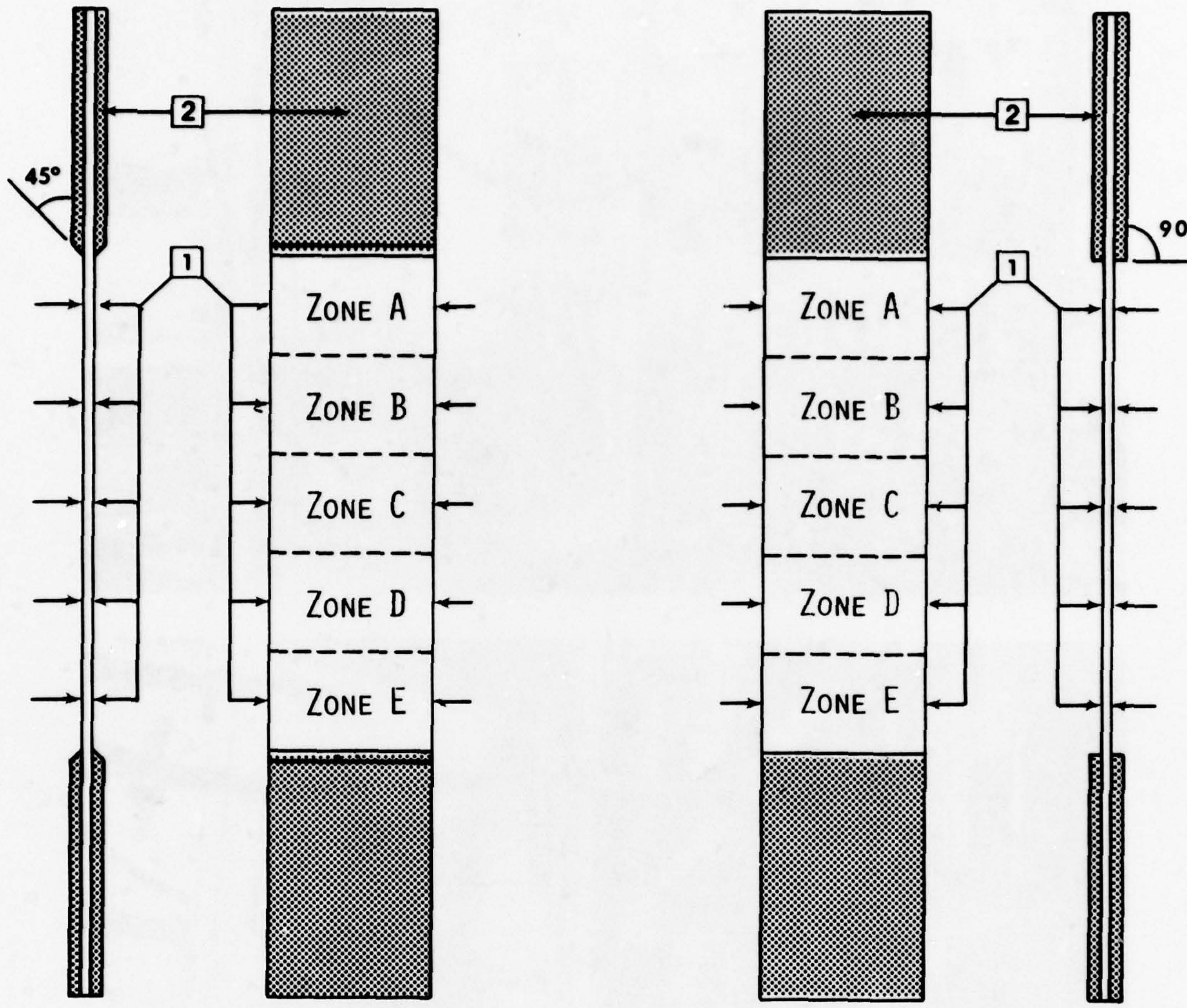


FIGURE 1d. PHOTOMICROGRAPH OF [$0/0/90/\pm 45$]$_S$
LAMINATE (100X).



a) STATIC SPECIMEN b) FATIGUE SPECIMEN

* SPECIMENS ARE 2.5 CM WIDE AND 15 CM LONG WITH 7.5 CM OF GAGE SECTION.

[1] SPECMEN THICKNESS AND WIDTH ARE OBTAINED FROM THE AVERAGE OF FIVE MEASUREMENTS, MADE AT THE MID-POINT OF EACH ZONE (1.5 CM APART.)

[2] TABS TO BE CUT FROM AN 0.16 CM-THICK GLASS FABRIC.

FIGURE 2. SPECIMEN CONSTRUCTION.

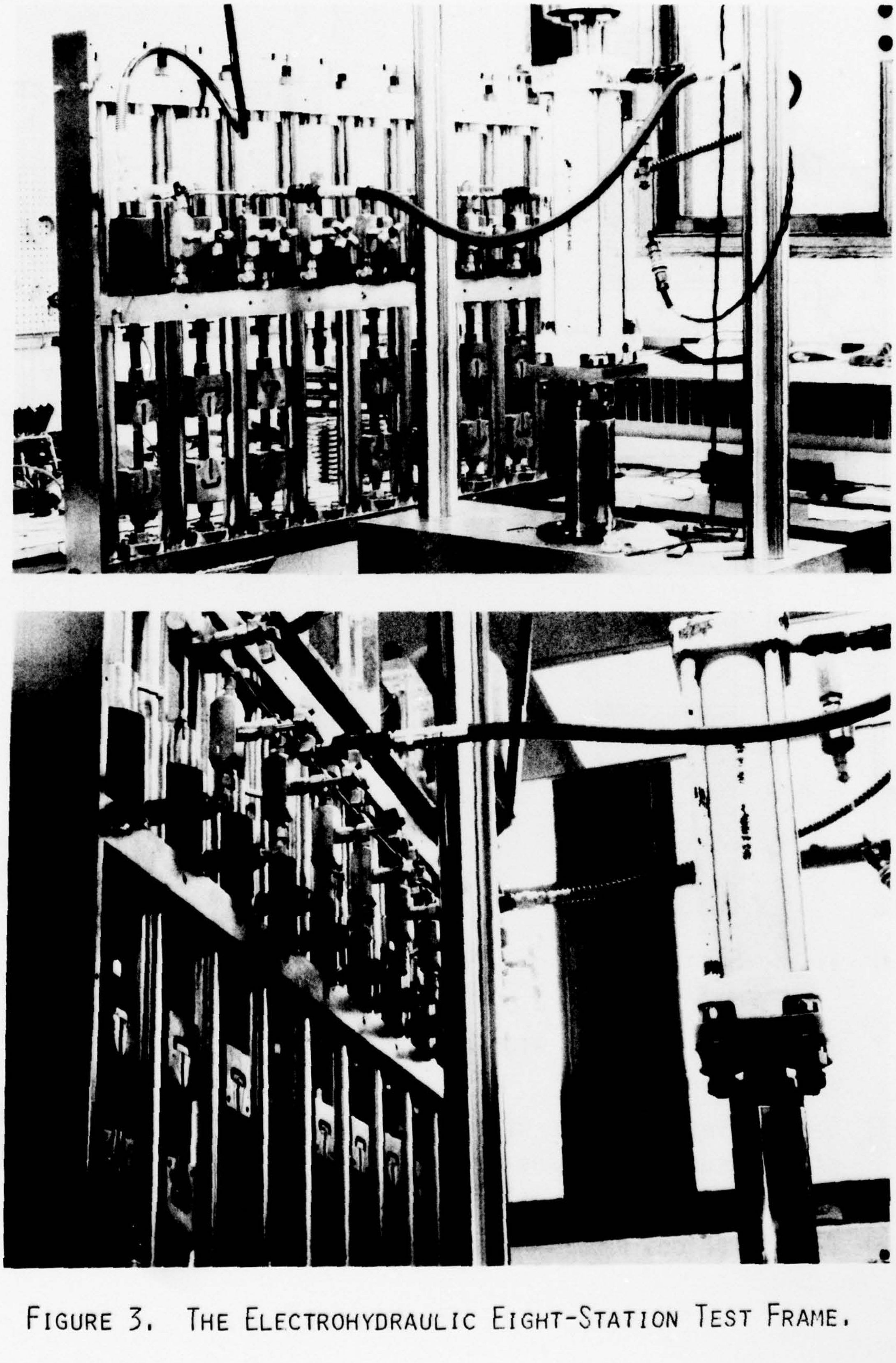
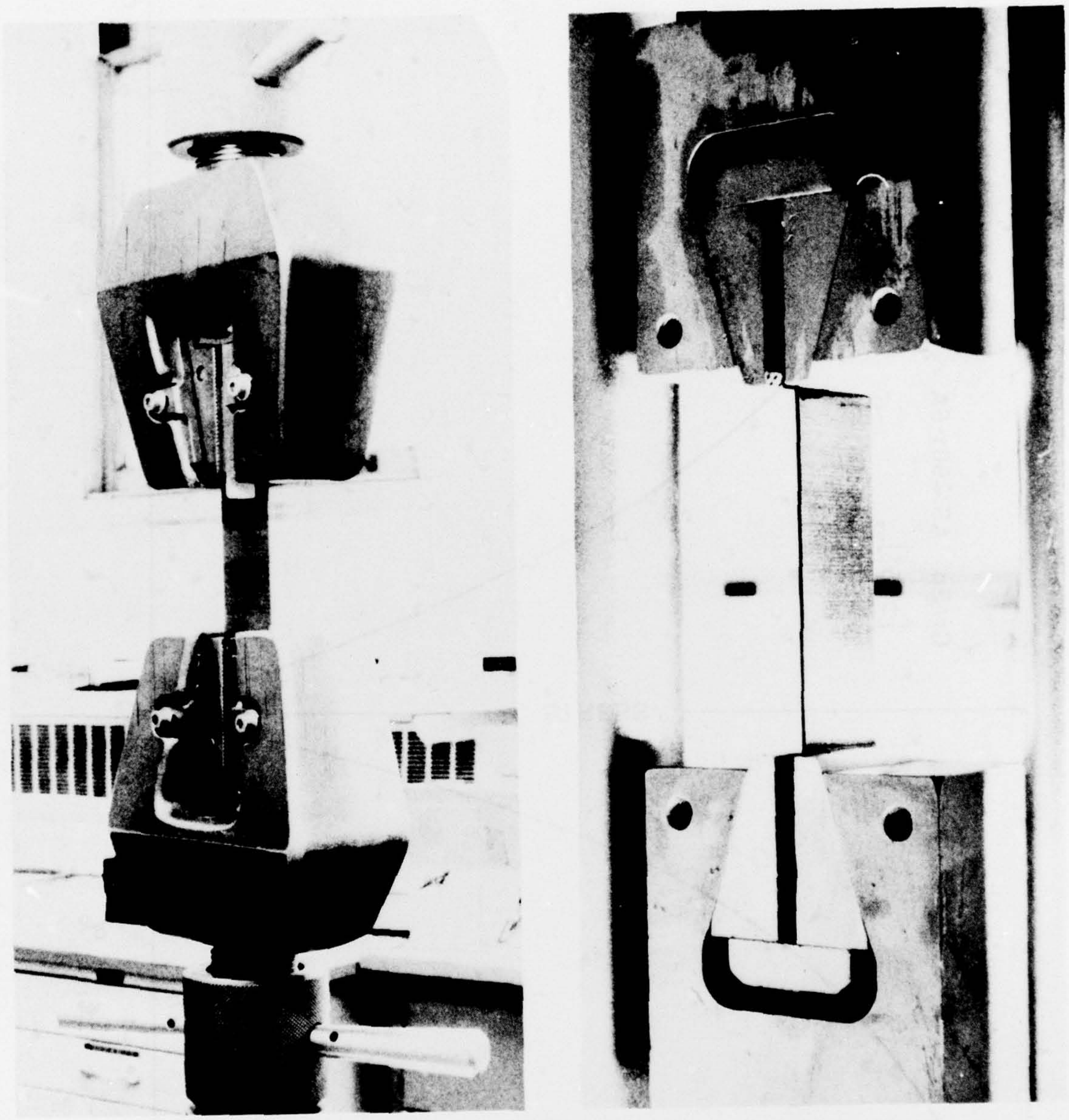


FIGURE 3. THE ELECTROHYDRAULIC EIGHT-STATION TEST FRAME.



a) Static Test   **b)** Fatigue Test

Figure 4. Mounting Jigs.

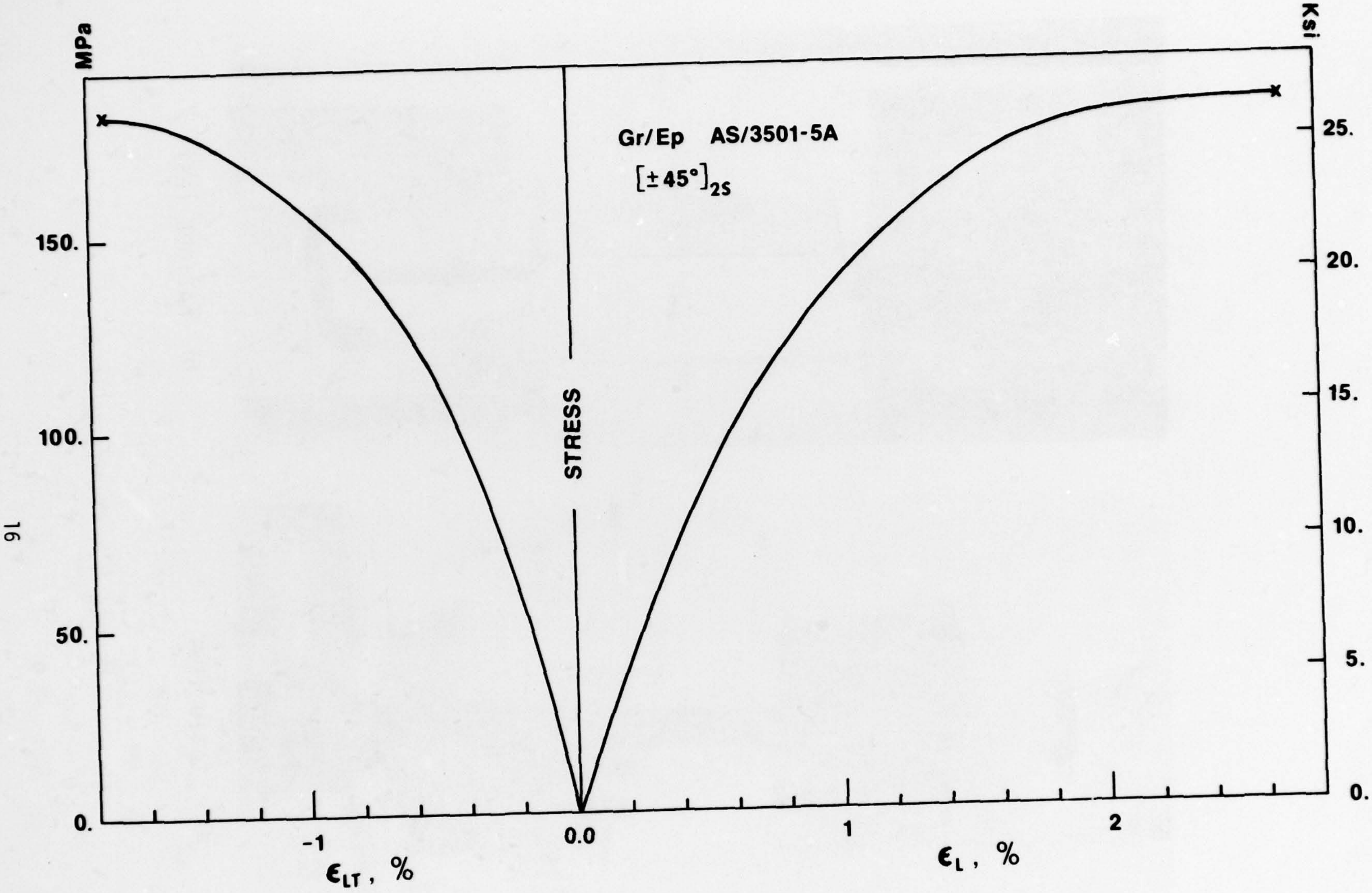


FIGURE 5. STRESS-STRAIN RESPONSE OF $[\pm 45^{\circ}]_{2S}$ LAMINATE.

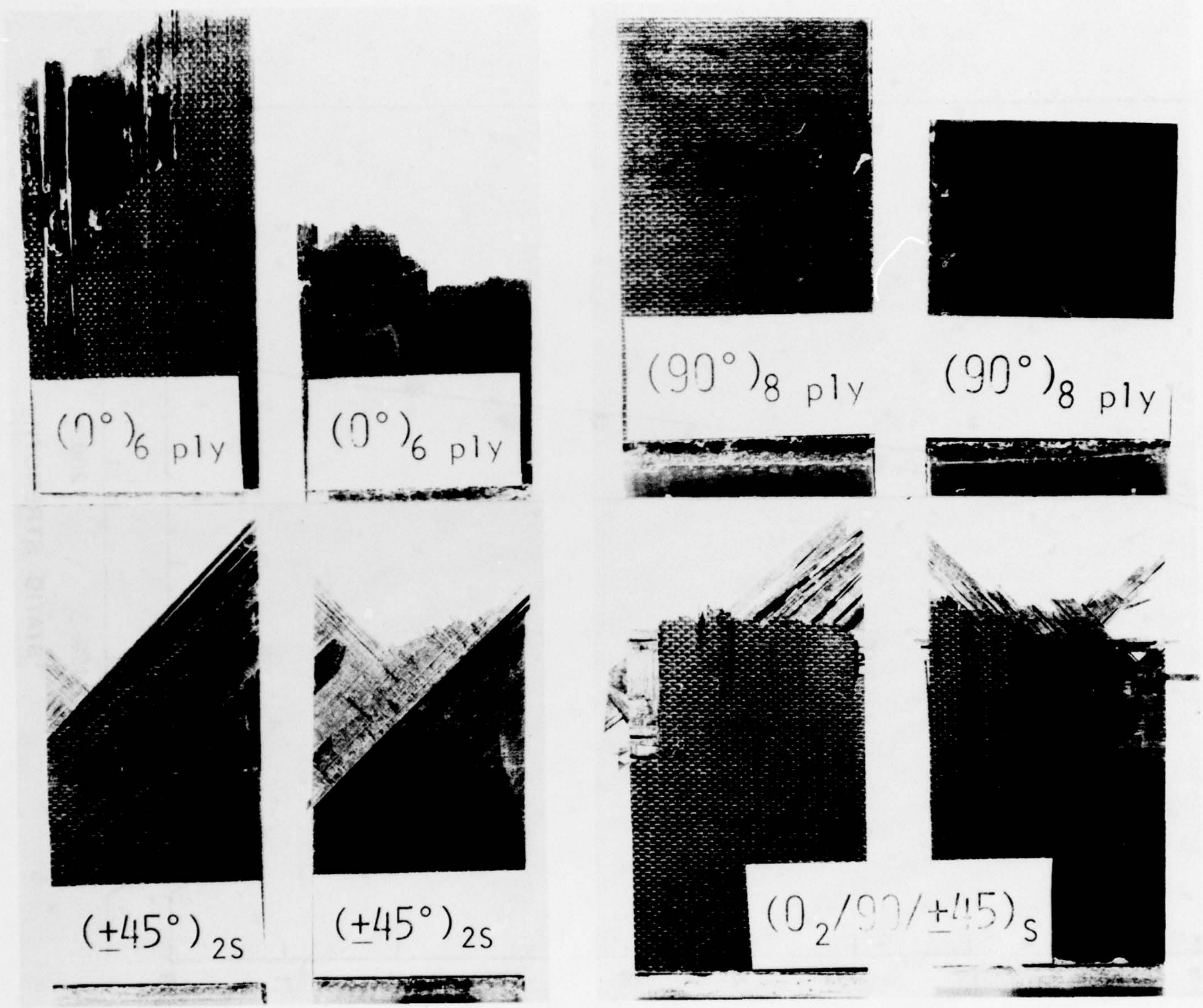


FIGURE 6. FAILURE MODES OF STATIC SPECIMENS.

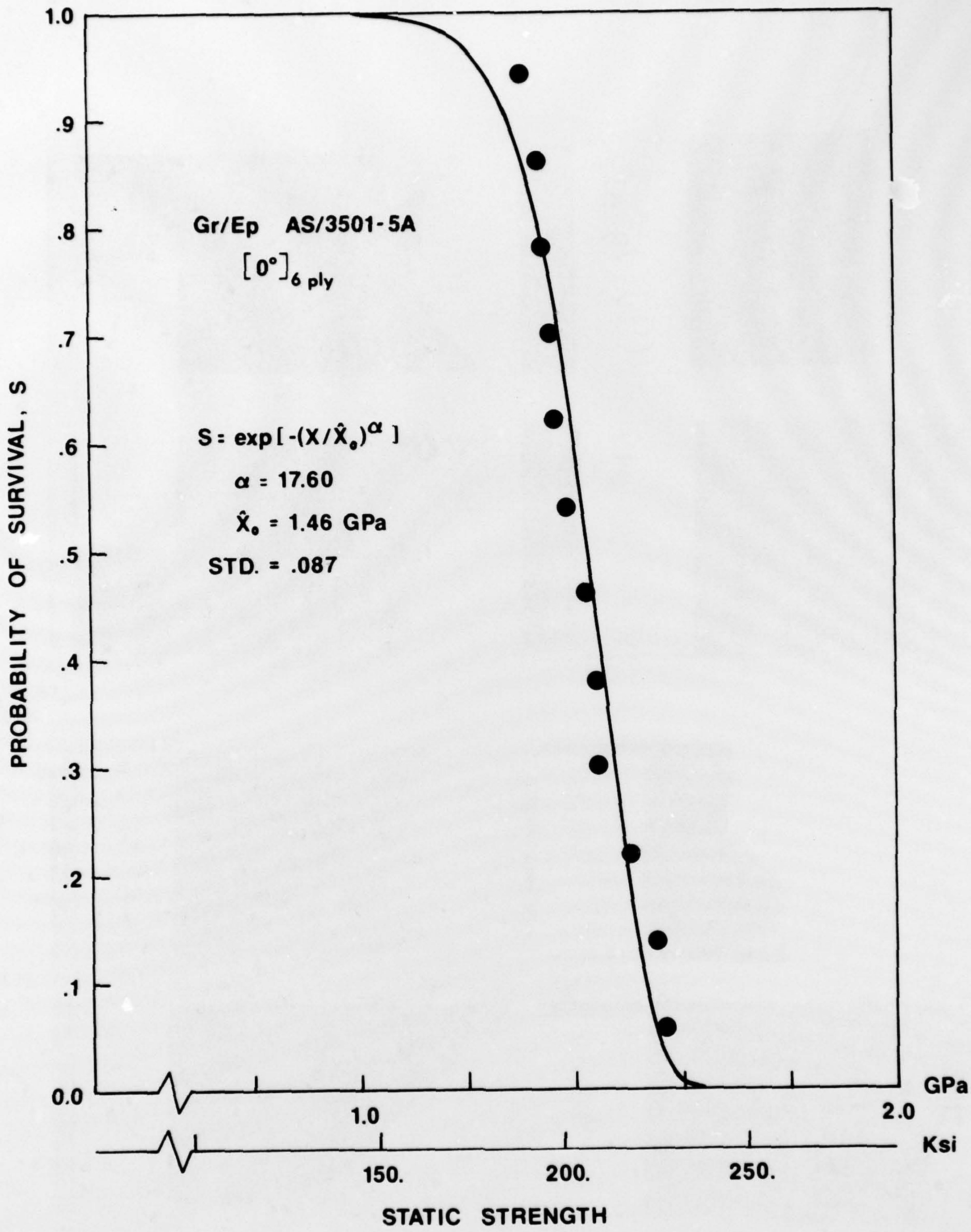


FIGURE 7. STATIC STRENGTH DISTRIBUTION OF $[0°]_{6\ ply}$ LAMINATE.

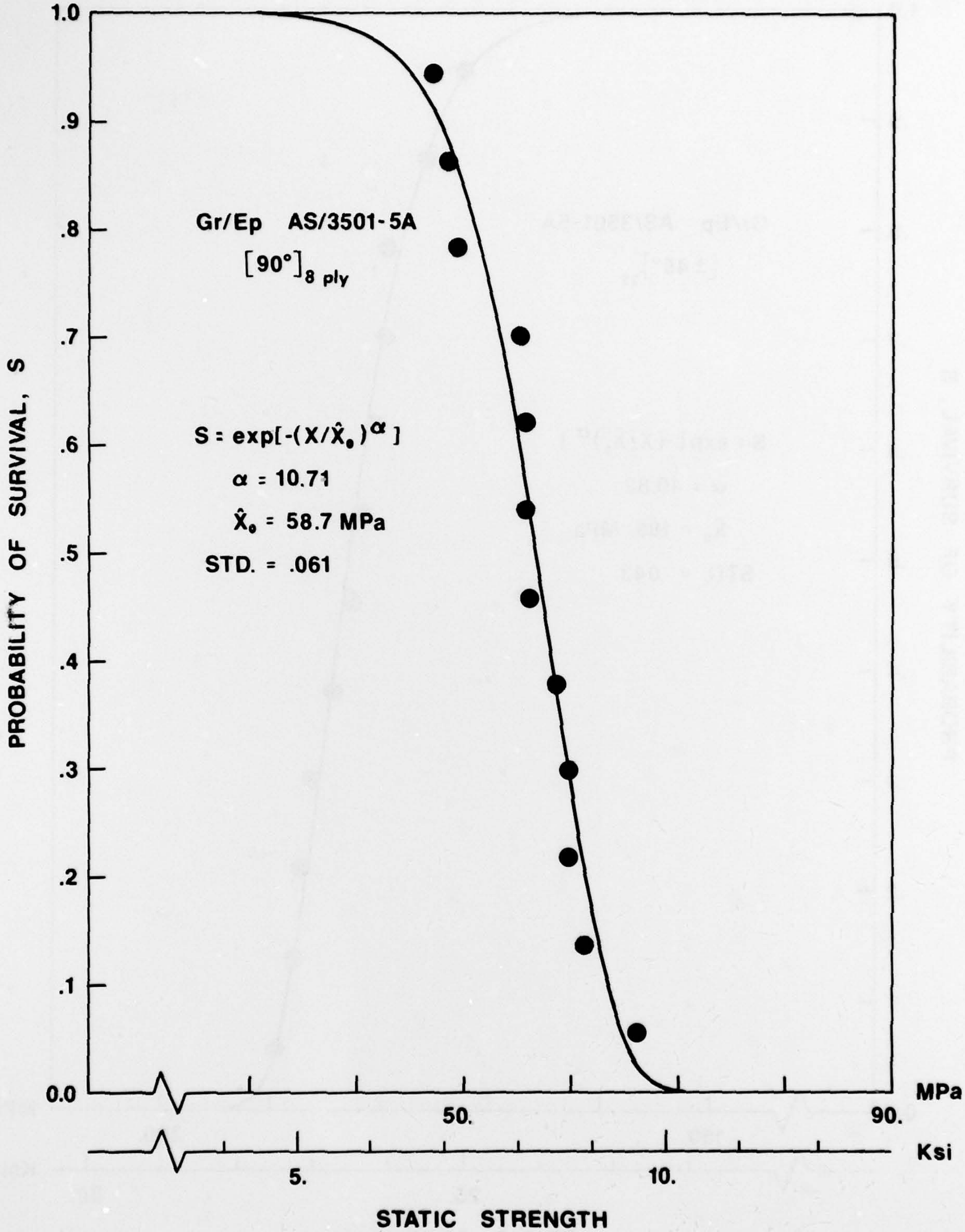


FIGURE 8. STATIC STRENGTH DISTRIBUTION OF $[90°]_{8\ ply}$ LAMINATE.

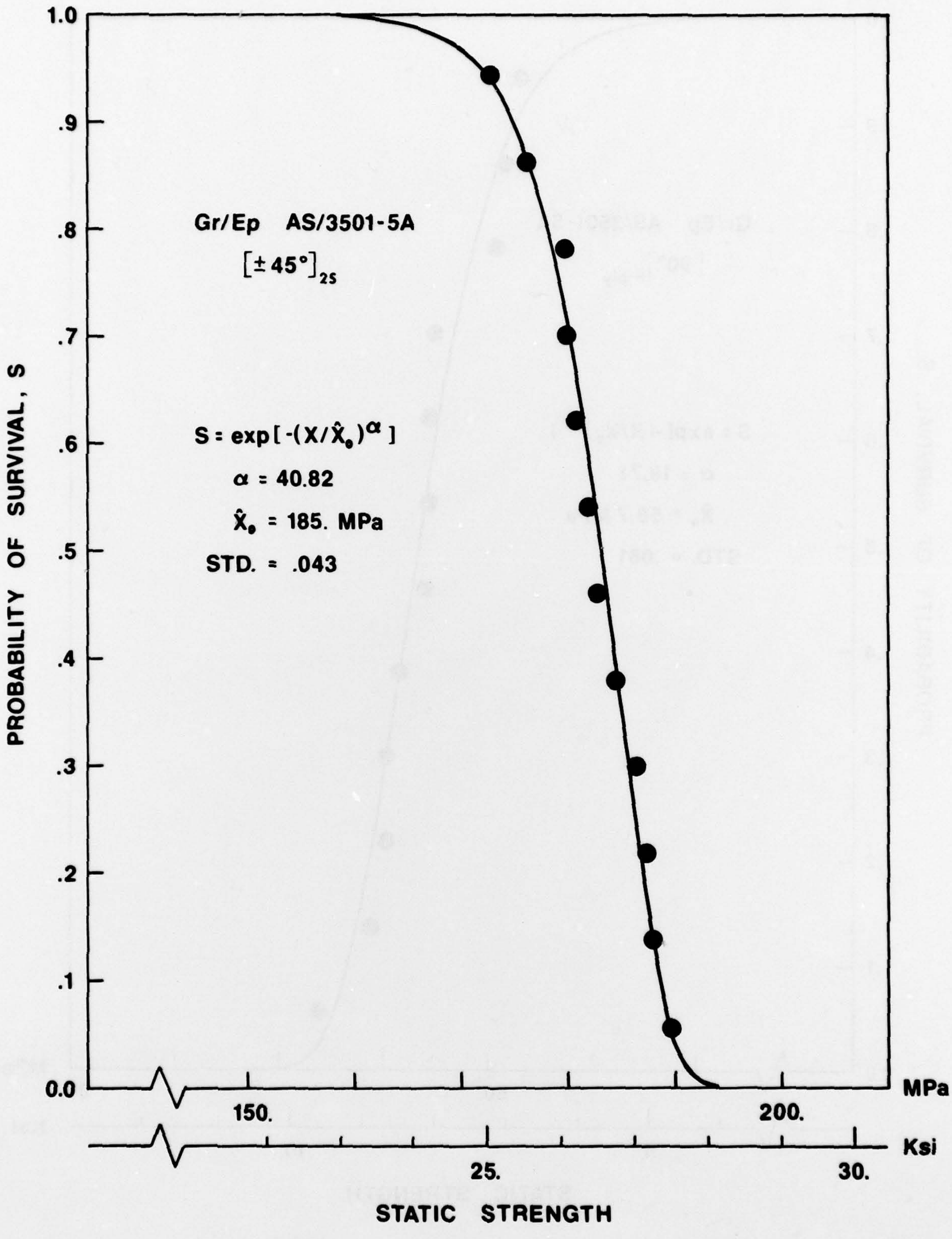


FIGURE 9. STATIC STRENGTH DISTRIBUTION OF $[\pm 45°]_{2S}$ LAMINATE.

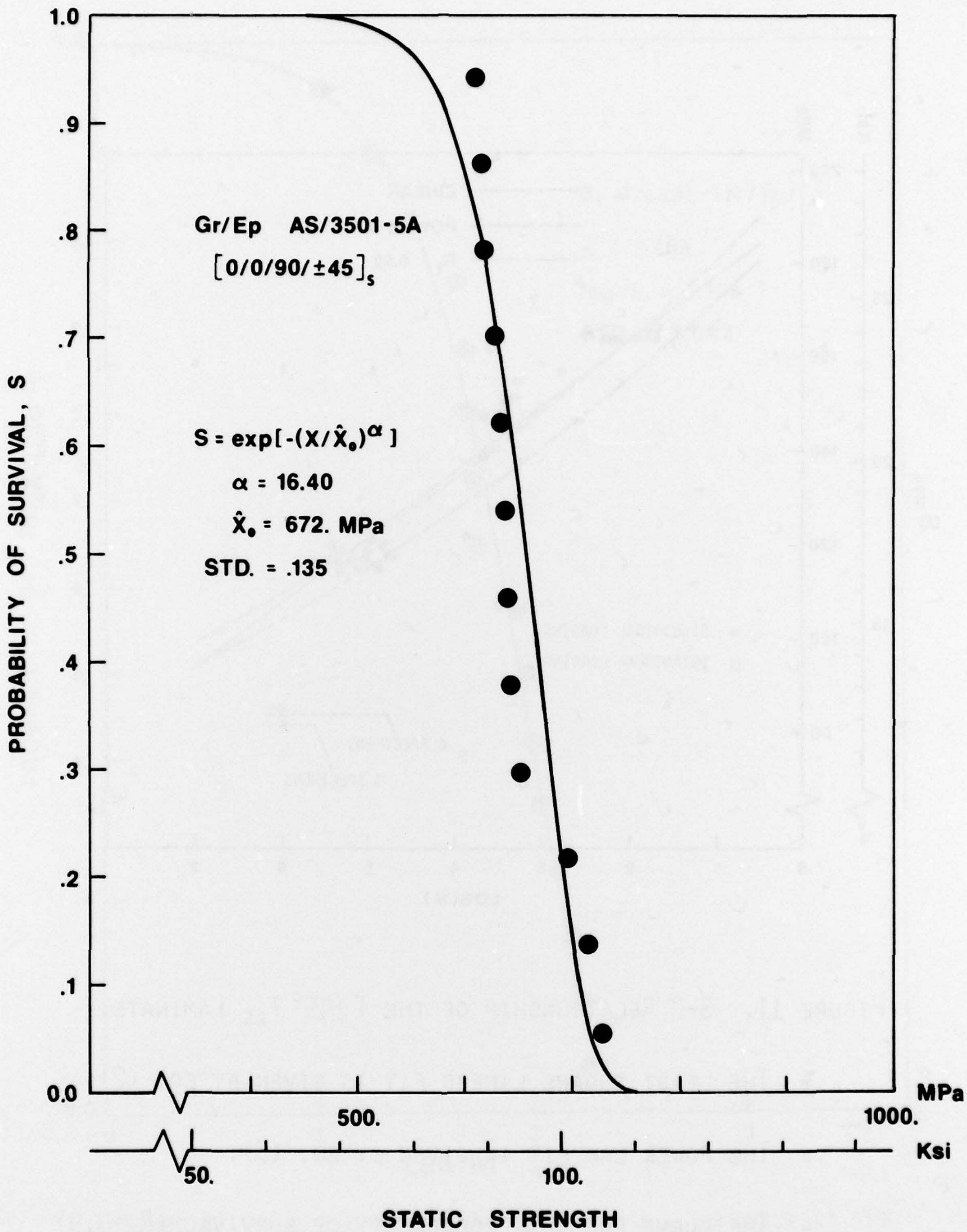


FIGURE 10. STATIC STRENGTH DISTRIBUTION OF $[0/0/90/\pm45]_S$ LAMINATE.

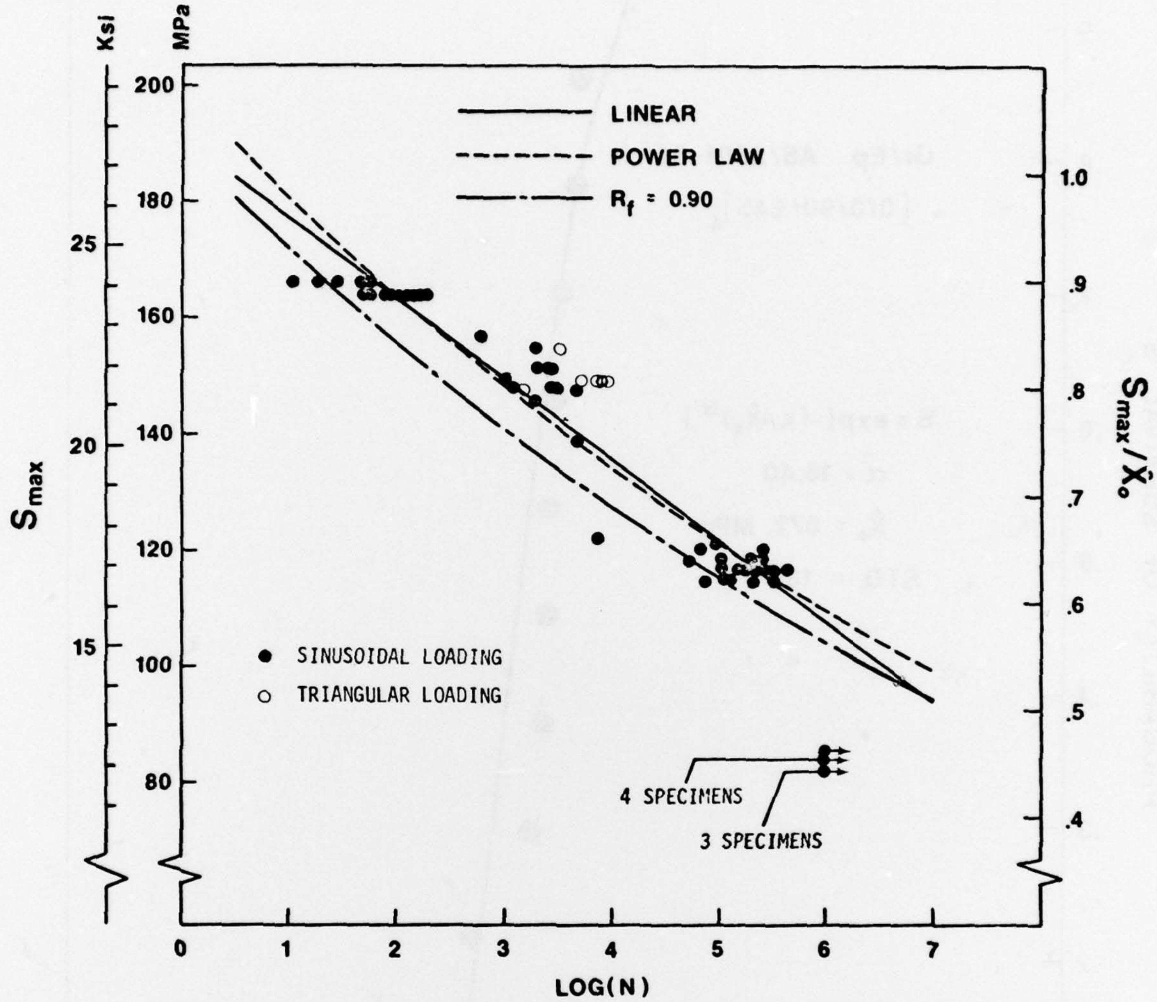


FIGURE 11. S-N RELATIONSHIP OF THE $[\pm 45^\circ]_{2S}$ LAMINATE.

* THE LEAST SQUARE LINEAR FIT IS GIVEN BY EQ. (2).

* THE POWER LAW FIT IS GIVEN BY EQ. (3).

* THE CURVE FOR 90% PROBABILITY OF SURVIVAL (R_f=0.9) IS OBTAINED FROM EQ. (5).

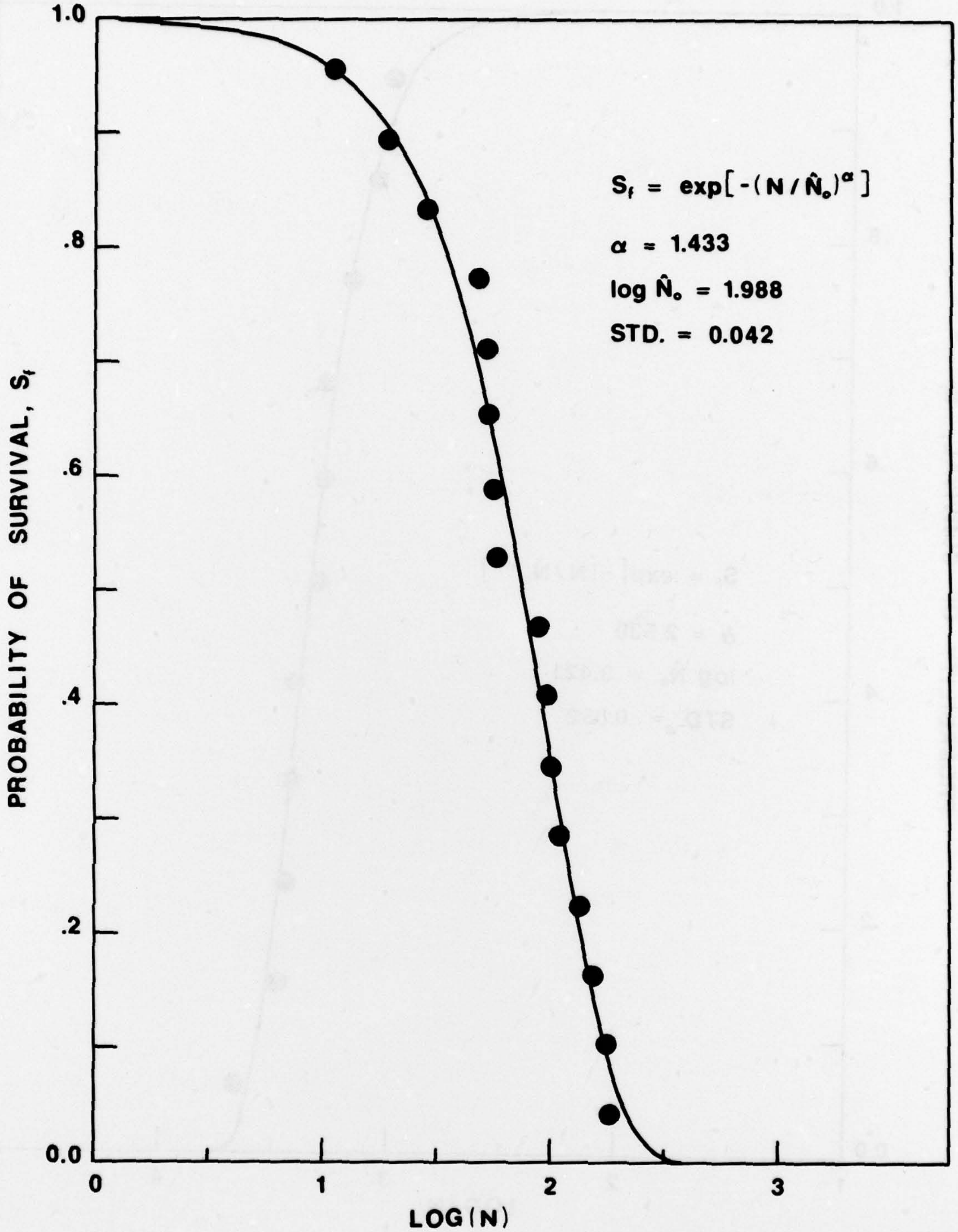


FIGURE 12. LIFE DISTRIBUTION OF $[\pm 45^\circ]_{2S}$ LAMINATE AT THE APPLIED STRESS LEVEL $S_{max}/\hat{X}_o \simeq 90\%$.

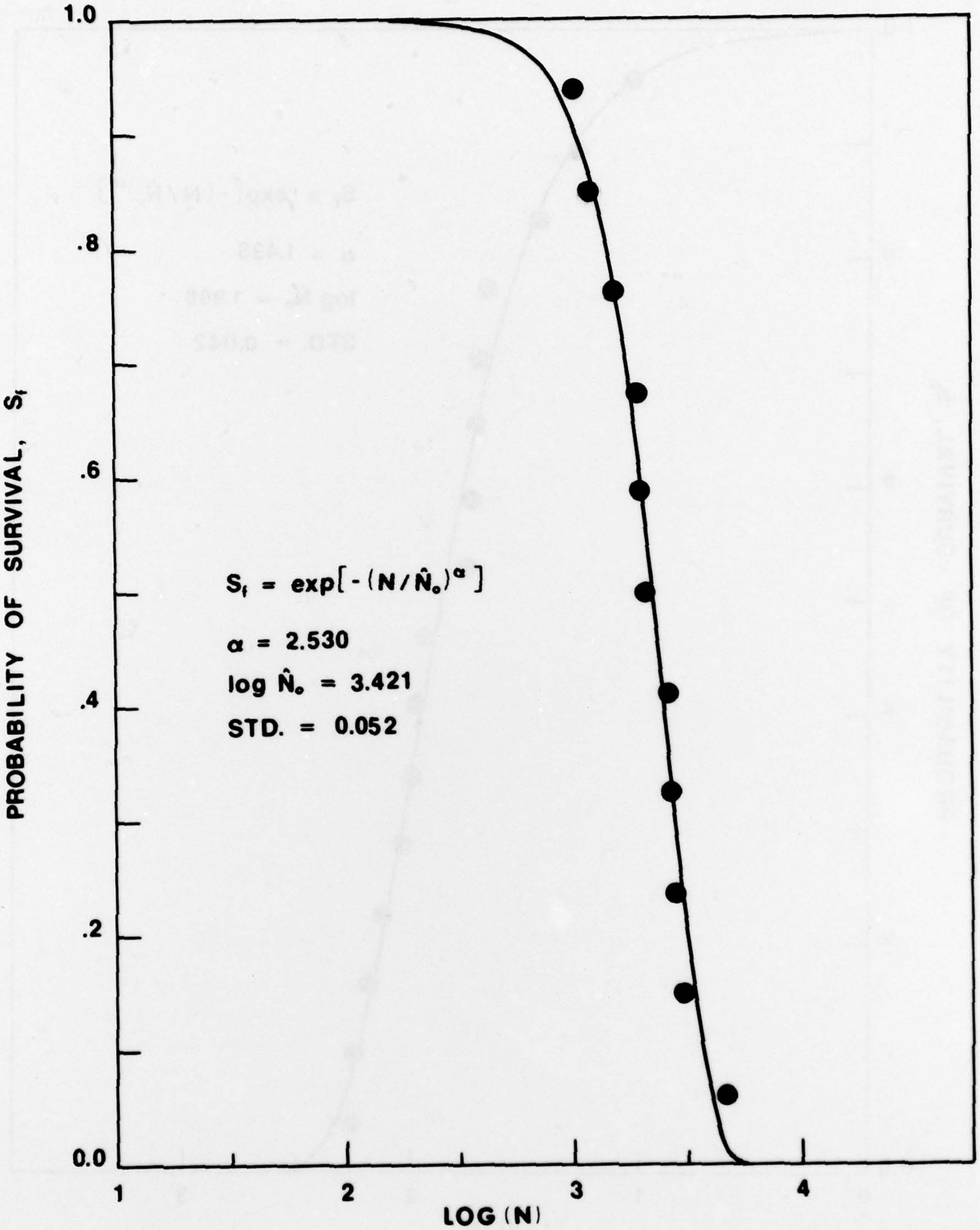


FIGURE 13. LIFE DISTRIBUTION OF $[\pm 45^\circ]_{2S}$ LAMINATE AT THE APPLIED STRESS LEVEL $S_{max}/\hat{X}_o \simeq 80\%$.

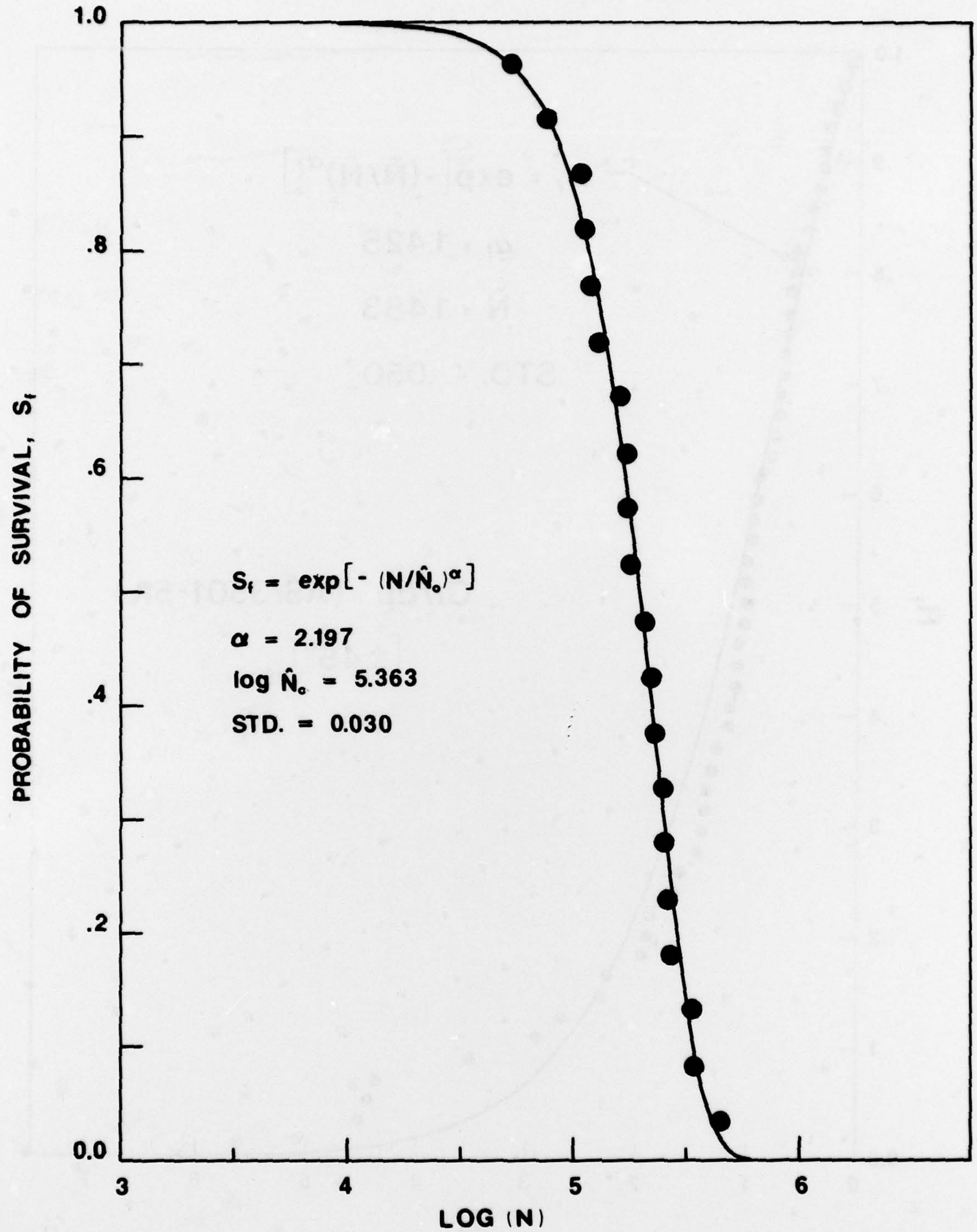


FIGURE 14. LIFE DISTRIBUTION OF $[\pm 45^0]_{2S}$ LAMINATE AT THE APPLIED STRESS LEVEL $S_{max}/\hat{X}_o \simeq$ 60%.

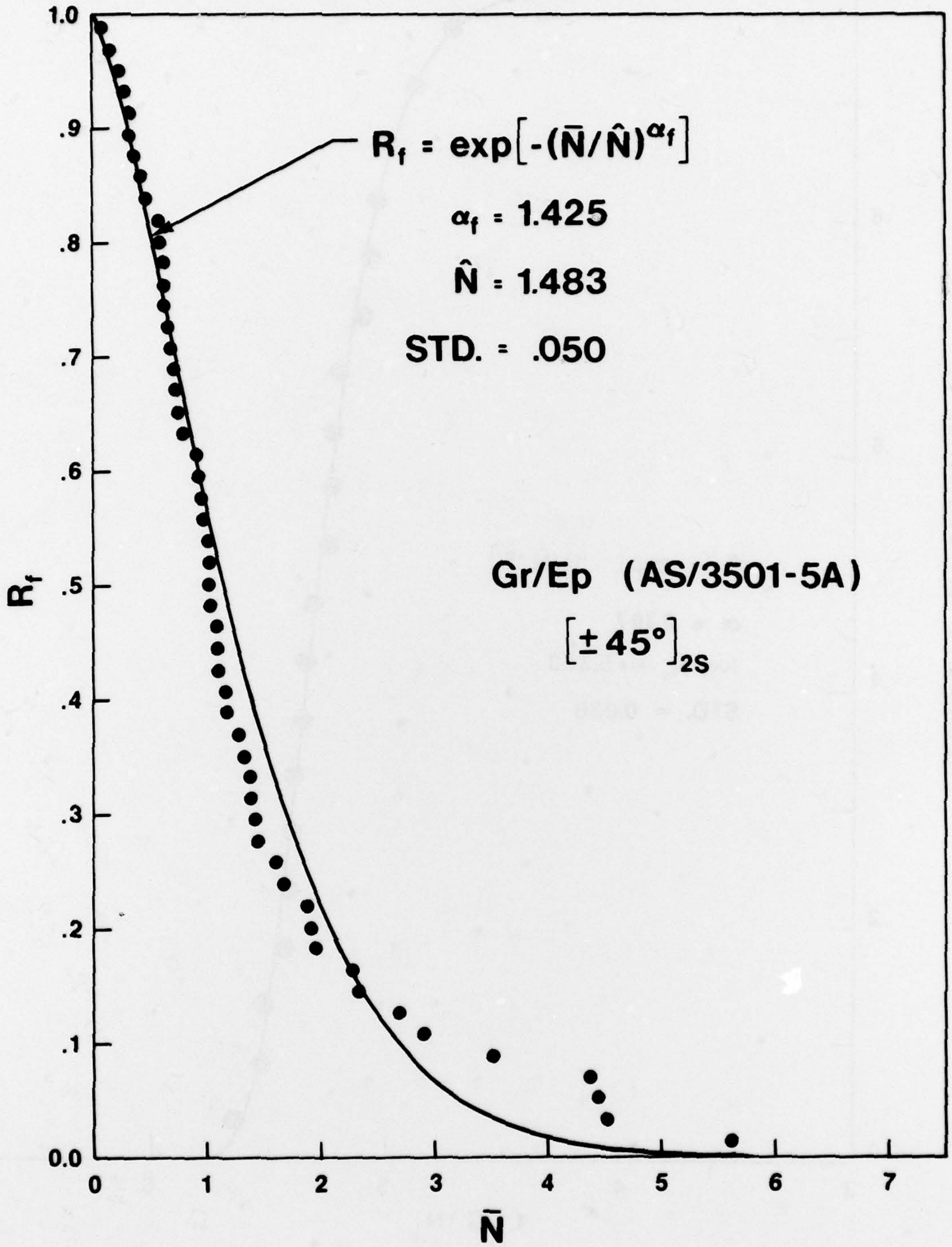


FIGURE 15. LIFE DISTRIBUTION FOR POOLED LIFE DATA OF THE $[\pm 45°]_{2S}$ LAMINATE. $\bar{N}$ IS NORMALIZED LIFE.

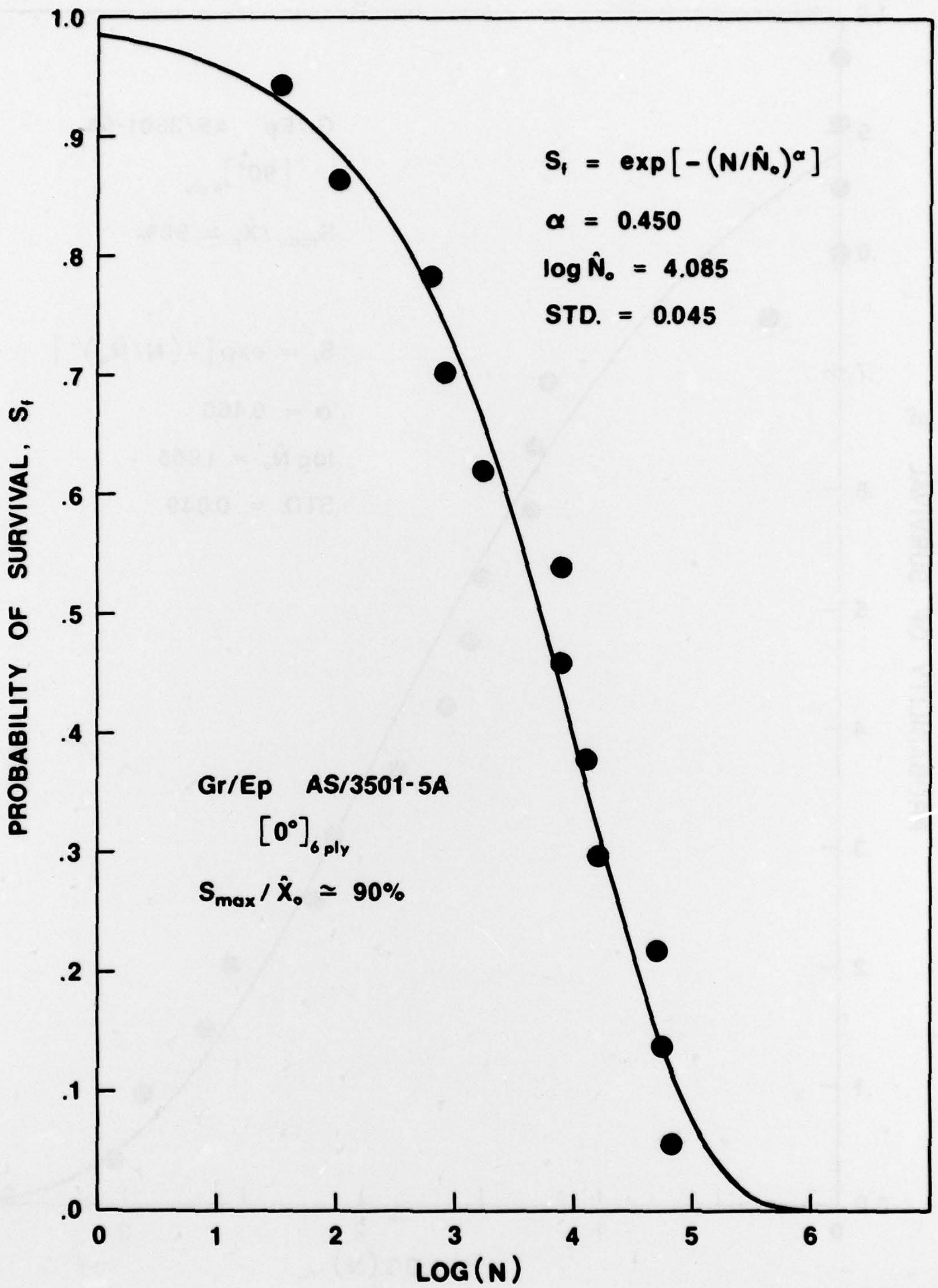


FIGURE 16. LIFE DISTRIBUTION OF $[0°]_{6\ ply}$ LAMINATE AT THE APPLIED STRESS LEVEL $S_{max}/\hat{X}_o \simeq 90\%$.

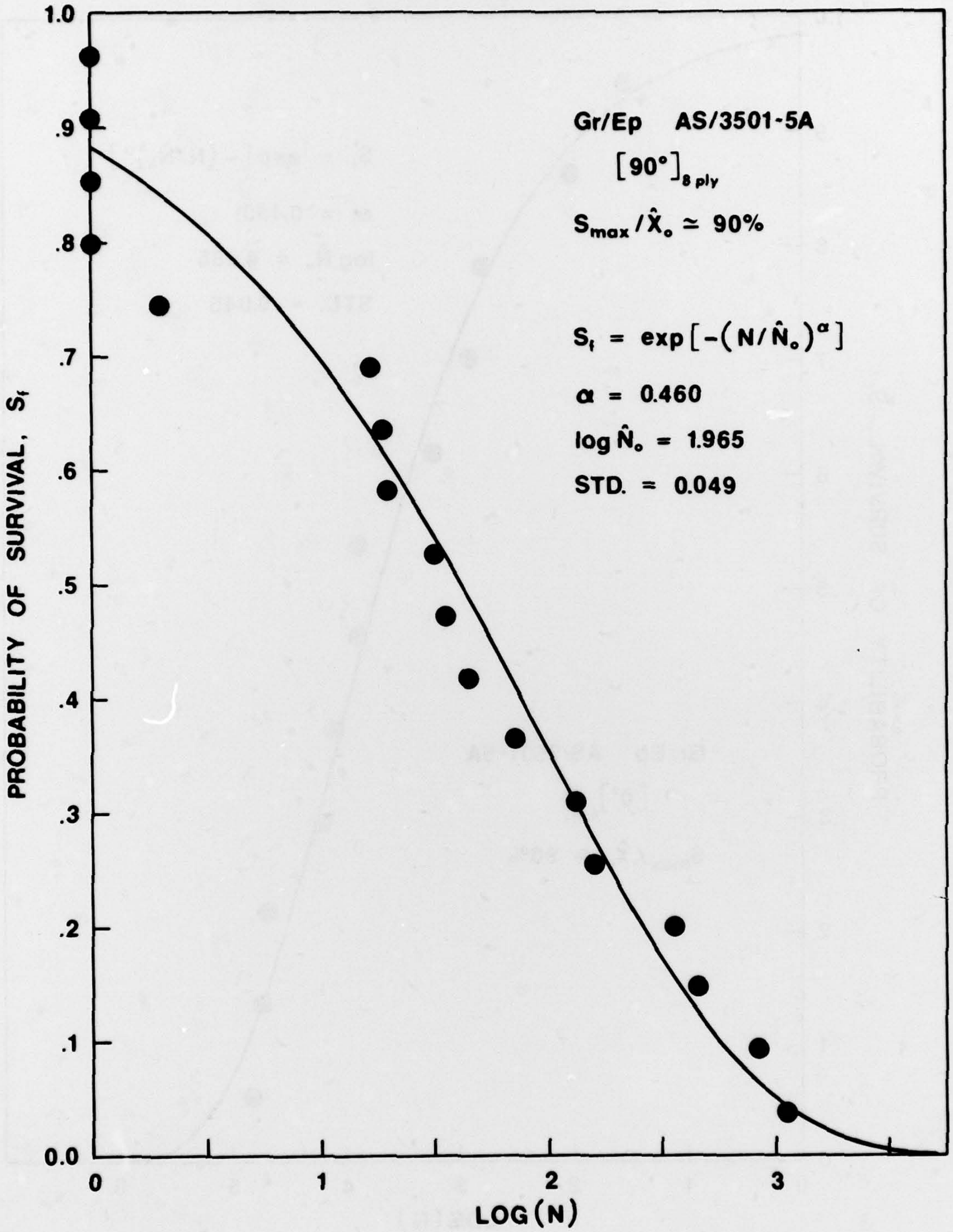


FIGURE 17. LIFE DISTRIBUTION OF $[90°]_{8\,ply}$ LAMINATE AT THE APPLIED STRESS LEVEL $S_{max}/\hat{X}_o \simeq 90\%$.

☆U.S.Government Printing Office: 1979 — 657-002/92